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Natural recovery of moss-dominated biological soil crusts after surface soil removal and their long-term effects on soil water conditions in a semi-arid environment

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ABSTRACT

Biological soil crusts (BSCs) are extensively developed and commonly regarded as a kind of vegetation in desertification areas around the world. The natural recovery process of BSCs after disturbance and their long-term impacts on the soil water conditions are important but not well understood. In order to provide more insights into this problem, we set up two treatments including BSCs (natural BSCs without disturbance) and disturbed BSCs (the top 30 mm of surface soil, including the BSC layer, was severely disturbed and completely removed) in a semi-arid environment on the Loess Plateau of China. Over the succeeding years, the natural recovery process of BSCs was qualitatively described and the soil water content at 0–90 cm depth of the two treatments was consecutively monitored. The results showed the following: (1) it is possible to recover natural moss-dominated BSCs after severe disturbance under natural conditions, and the recovery process to BSC full-coverage took approximately three years; (2) the BSC disturbance greatly decreased soil water content by up to 18% and the effects gradually weakened with time; (3) the BSC disturbance decreased surface soil water content (0–70 cm) by up to 24% but increased deep soil water content (80–90 cm) by up to 13%; and (4) the BSC disturbance decreased soil water storage at 0–90 cm by 7.8 mm, 4.4 mm, 8.0 mm, and 4.9 mm in the second, third, fourth, and seventh years, respectively. We concluded that the BSC disturbance degraded soil water conditions in the three to four years following the disturbance. Therefore, the artificial destruction of natural moss-dominated BSCs in a semi-arid region on the Loess Plateau of China should not be recommended as a land management practice for the improvement of soil water conditions.

1. Introduction

Desertification and land degradation due to climate variability and human activities in arid and semi-arid regions are some of the greatest environmental challenges today (Helldén and Tottrup, 2008; Johnson et al., 2006; Thai et al., 2007; Verstraete et al., 2009). Throughout the world, desertification affects more than two billion people and the 36 million square kilometers of desertified land accounts for approximately 1/4 of the earth's surface area (Johnson et al., 2006; Thai et al., 2007). Owing to the extreme scarcity of water resources in such areas, the degradation of vascular plants and the irreversible rapid decrease in vegetative coverage become the most important characteristics of desertification (Asner and Heidebrecht, 2005). In some desertified areas (e.g., the Loess Plateau of China), vegetation covers approximately 5% of the area as a result of long-term shortages in precipitation, intense evaporation, and severe soil and water loss (Wang et al., 2008; Xin et al., 2008). However, in the open space between the sparse vegetation in such areas, biological soil crusts (BSCs), which are defined as the complex mosaic of soil, green algae, lichen, moss, micro-fungi, cyanobacteria, and other bacteria by Belnap and Lange (2003), are extensively developed and are widely distributed in hot, cool, and cold arid and semi-arid regions (Belnap and Lange, 2003). BSCs usually cover up to 40–100% of the open ground surface and become one of the most important components of vegetation and land cover in desertified areas (Clair et al., 1993; Xiao et al., 2011b).

The ecological functions of BSCs and their potential effects on desertification are attracting more attention, and recently, they have been recognized as a major influence on desert terrestrial ecosystems (Belnap, 2006; Bowker et al., 2011; Maestre et al., 2011; Tisdall et al., 2012). Some physical, chemical, and biological properties of surface soil, such as roughness, texture, porosity, absorptivity, color, organic matter, fertility, hydraulic parameters, biodiversity and activity are greatly influenced by BSCs (Chamizo et al., 2012; Duan et al., 2007; Eldridge and Leys, 2003; Fischer et al., 2010; Guo et al., 2008; Housman et al.,

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2006; Menon et al., 2011; Rodríguez-Caballero et al., 2012; Xiao et al., 2007; Zhao et al., 2010). Although there are some positive effects of BSCs on desert terrestrial ecosystems, including increasing soil carbon and nitrogen (Belnap et al., 2003; Chamizo et al., 2012; Green et al., 2008), improving soil stability against water and wind erosion (Bowker et al., 2008; Guo et al., 2008; Rodríguez-Caballero et al., 2012; Tisdall et al., 2012), increasing infiltration and reducing runoff and evaporation in semi-arid cool and cold regions (Belnap, 2006; Belnap et al., 2005; Xiao et al., 2011b; Zhang et al., 2008), the negative effects of BSCs have also been reported by many researchers. For example, BSCs smooth the soil surface and prevent plant seeds from penetrating the soil under natural conditions, and they make it difficult for seed roots to penetrate the surface soil (Beyschlag et al., 2008; Deines et al., 2007; Hawkes, 2004; Langhans et al., 2009; Li et al., 2005; Serpe et al., 2006; Su et al., 2007). For this reason, the quantity and diversity of the plant community is significantly decreased by the presence of BSCs (Green et al., 2008). In many cases, BSCs reduce water infiltration (e.g., in hyperarid and most warm arid and semi-arid regions (Coppola et al., 2011; Malam Issa et al., 2011)), increase water evaporation (Chamizo et al., 2013; Kidron and Tal, 2012), and ultimately, they degrade deep soil water conditions (Eldridge and Leys, 2003; Xiao et al., 2007), which are originally available for vascular plant growth.

To avoid the above negative effects of BSCs in a desertified area, scientists and land managers have suggested that BSCs should be artificially destroyed periodically by crushing the BSC layer or partly removing the BSC layer by hand or machinery (Belnap and Lange, 2003). Moreover, BSCs would also be severely disturbed as a side effect of the removal of physical crusts underneath BSCs, which are characterized by very limited infiltrability (Badorreck et al., 2013; Fox et al., 2004). It has reported that BSCs are highly sensitive to surface disturbance and soil burial, which are caused by unintentional acts from human trampling, livestock, off-road vehicles, and engineering activities (Belnap et al., 2003; Dojani et al., 2011; Green et al., 2008; Langhans et al., 2010; Read et al., 2011). The natural recovery process of BSCs after disturbance and their long-term ecological impacts on desertified ecosystems, especially on the soil water conditions that limit plant degradation and re-vegetation, are important but not well understood.

In this study, an experimental site with well-developed natural BSCs was selected in a semi-arid environment, representative of climate and desertification on the Loess Plateau of China; then two treatments including BSCs (natural BSCs without disturbance) and disturbed BSCs (the top 30 mm of surface soil, including the BSC layer, was severely disturbed and completely removed) were set up in 2005. After that, the natural recovery process of BSCs was qualitatively described, and the soil water content at 0–90 cm depth of the experimental plots with the BSCs and the disturbed BSCs was monitored from 2006 to 2011. Using the soil water content data, the long-term effects of BSC disturbance on soil water conditions were quantitatively determined between the BSCs and the disturbed BSCs. The objectives of this study were to answer the following questions. (1) Is it possible to recover moss-dominated BSCs after severe disturbance under natural conditions without any additional manipulation? How long does it take? (2) What are the impacts of BSC disturbance on soil water conditions in semi-arid environments? How long do these impacts last? (3) How do soil water conditions change during the recovery process of BSCs after disturbance? It was hoped that the results could give useful information about the optimal use of limited soil water resources and the management of BSCs in desertified area, and that the results could be helpful for re-vegetation in arid and semi-arid environments on the Loess Plateau of China.

2. Study area

The study was conducted in the Liudaogou watershed (38°46′–38°51′ N latitude and 110°21′–110°23′ E longitude, Fig. 1A) on the Loess Plateau of China. The average annual precipitation is 409 mm, and the precipitation from June to September accounts for 80% of the annual precipitation (Cha and Tang, 2000). The average annual potential evaporation is 1337 mm, which is more than three times the local precipitation. The annual mean temperature is 8.4 °C with the highest mean temperature of 23.7 °C in summer and the lowest mean temperature of −9.7 °C in winter. Drought followed by concentrated rainfall, sparse vegetation, loose soils, complex landform, and poor land use practices since the 17th century has resulted in severe soil erosion and water shortages resulting from runoff water losses (Cha and Tang, 2000; Xiao et al., 2011a). This region experiences the most serious soil erosion in the Loess Plateau and is the main source for coarse sediment in the Yellow River (Cha and Tang, 2000). Natural moss-dominated BSCs are extensively developed on fallow lands, shrub lands, and

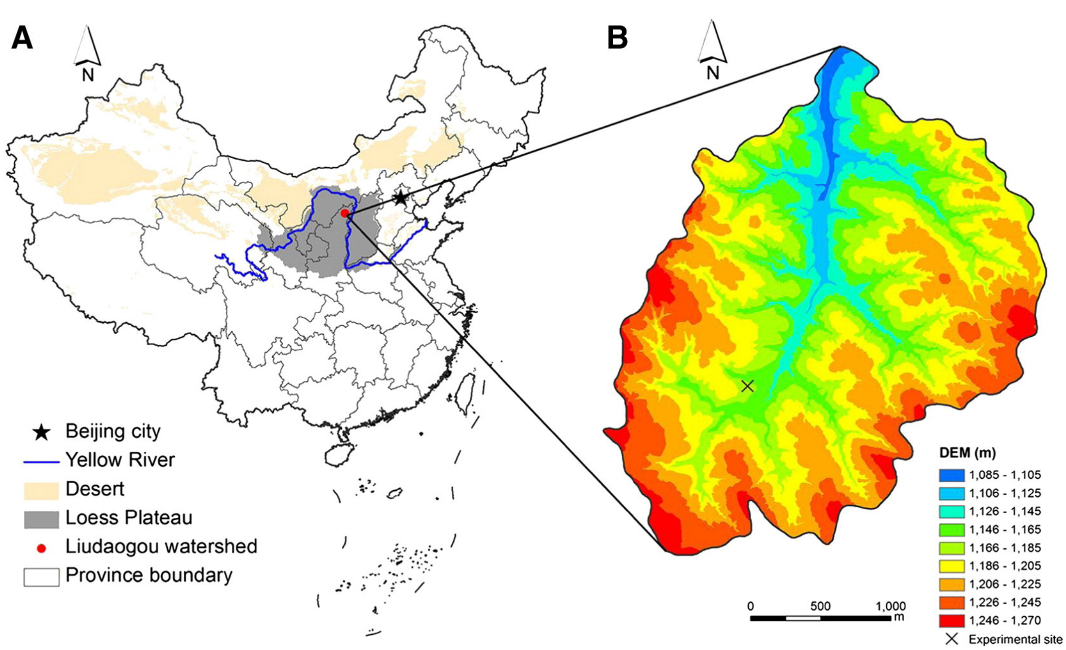

Fig. 1. Location of (A) the Liudaogou watershed on the Loess Plateau of China and (B) the experimental site in the watershed.

grasslands on the watershed, with a coverage reaching 70–80% (Xiao et al., 2010).

A representative very sparse shrub land with a 5° north-east facing slope and 20-year-old natural BSCs was selected as an experimental area in the Liudaogou watershed (Fig. 1B). The BSCs in this region are dominated by mosses *Bryum arcticum* (R. Brown) B.S.G. and *Didymodon vinealis* (Brid.) Zander (Xiao et al., 2010). The soil was a loess soil (Ust-Sandic Entisols), and its texture was loamy sand with 81% sand, 14% silt, and 5% clay. The top soil (0–20 cm) pH, organic matter, total nitrogen and phosphorus were 8.7, 0.3%, 0.1 g kg^{-1} and 0.4 g kg^{-1}, respectively. Correspondingly, the available nitrogen, phosphorus, and potassium were 18.8 mg kg^{-1}, 5.5 mg kg^{-1}, and 84.0 mg kg^{-1}, respectively.

3. Methods

Two independent variables were considered in this study: BSCs (two levels: BSCs and disturbed BSCs) and time (covering a total of 38 field campaigns conducted after the BSC disturbance). According to the experimental design, two treatments (BSCs and disturbed BSCs) with three replications were set up, and corresponding six hydraulically isolated experimental plots with a 5 m length and a 3 m width were established randomly on the experimental area before the onset of the rainy season in 2005 (June 26). On the disturbed BSC plots, approximately 30 mm of soil including the BSC layer was severely disturbed and then completely removed by hand, and the soil surface was smoothed to an even 5° slope. Afterwards, the soil surface situations and soil water conditions of the two treatments were monitored under natural conditions without any management practices including irrigation, fertilization, weeding, and sun-shading. Moreover, runoff was considered in the experimental design, but actually there was no runoff recorded under natural rainfall conditions due to the high infiltration rate of the loamy sand soil and limited rainfall intensity in the study area.

Two characteristics were measured in this study: the recovery of BSCs after the disturbance and the soil water content at different depths. These two parameters were measured by the following methods. (1) The recovery and development process of BSCs after the disturbance was qualitatively described by their appearance, distribution, and coverage. Photographs of the soil surface were taken using a high resolution digital camera at different times, and then the BSC coverage was calculated from the pictures using supervised classification in ERDAS IMAGINE 8.7, then validated and corrected according to personal experience (Xiao et al., 2011b). The BSC coverage of each plot came from the mean value of more than five sites which were randomly and uniformly distributed on the plot. (2) Three plastic access tubes were installed at each plot for the BSCs and the disturbed BSCs. Through these tubes, the volumetric soil water content at 0–90 cm depth was measured at intervals of 10 cm with a time domain reflectometry probe (TRIME-IPH, IMKO in Germany). Measurements were conducted almost every month and lasted from 2006 to 2011 (in total, 38 field measurements after the BSC disturbance). In addition to the two parameters listed above, the amount and intensity of rainfall during the experiment were monitored with standard rain gages, and the potential evaporation was also measured by a water surface evaporator.

The soil water content of each plot was obtained from the mean values of the soil water content measured at the three tubes in the plot. The soil water storage (W) at different soil depths was calculated from the soil water content by the following equations.

$$W(L) = \sum_{10}^{L} \theta(L)/100 \times 100. \quad (1)$$

In this equation, $W(L)$ is the soil water storage at L depth, in mm; $\theta(L)$ is the volumetric soil water content at L depth, in %; and L is the soil depth that ranged from 10 to 90 at 10 cm intervals, in cm.

The effects of BSC disturbance were determined by the absolute difference of the soil water content (θ_E) and soil water storage (W_E) between the BSCs and the disturbed BSCs, defined as follows:

$$\theta_E(L) = \theta_{\text{disturbed BSCs}}(L) - \theta_{\text{BSCs}}(L) \quad (2)$$

$$W_E(L) = W_{\text{disturbed BSCs}}(L) - W_{\text{BSCs}}(L). \quad (3)$$

In these equations, $\theta_E(L)$ is the absolute difference of the soil water content at L depth between the BSCs and the disturbed BSCs, in %; $\theta_{\text{disturbed BSCs}}$ is the soil water content of the disturbed BSCs at L depth, in %; θ_{BSCs} is the soil water content of the BSCs at L depth, in %; $W_E(L)$ is the absolute difference of the soil water storage at L depth between the BSCs and the disturbed BSCs, in mm; $W_{\text{disturbed BSCs}}(L)$ is the soil water storage of the disturbed BSCs at L depth, in mm; and $W_{\text{BSCs}}(L)$ is the soil water storage of the BSCs at L depth, in mm.

The experimental data were analyzed based on descriptive statistics in SPSS 20, and the final results of each treatment come from the mean values of the three replications and expressed as the mean ± standard error. The differences between the BSCs and the disturbed BSCs were also statistically evaluated at 5% probability level by the repeated measurements ANOVA and the paired-samples t test in SPSS 20. The representation and graphical fits of experimental data were obtained using OriginPro 8.6.

4. Results

4.1. Natural recovery of BSCs after disturbance

A series of oblique pictures that reflect the natural recovery process of BSCs from zero to near full coverage after complete surface soil removal is presented in Fig. 2. Although more than 30 mm of surface soil including the BSC layer was completely removed and the soil surface was severely disturbed on June 26, 2005 (Fig. 2A), the disturbed soil surface quickly stabilized after a moderate rainfall event of approximately 20 mm (Fig. 2B) and a very thin structural crust (Rajot et al., 2003; Valentin and Bresson, 1992) of fine sand formed by the impact of raindrops. The structural crusts developed further with time and made the soil surface more and more stable (Fig. 2C and D). On the stabilized soil surface, moss communities slowly colonized and formed BSC patches (July 24, 2006, see Fig. 2E). The BSC patches increased with time (Fig. 2F to I) and finally developed to a near complete cover of BSCs on the soil surface by the end of 2007 (September 21, Fig. 2J). In the next years from 2008 to 2012, the recovered BSCs increased in density and thickness as well as became closer to the natural BSCs in appearance (Fig. 2K and L; the fine soil particles deposited on the soil surface in Fig. 2H to L were transported from the surrounding area by strong wind in winter and early spring rather than from the upper slope by runoff). As shown in Figs. 2 and 3, the BSCs almost fully (more than 90%) re-covered the soil surface three years after the severe disturbance under natural conditions.

4.2. Effects of BSC disturbance on soil water content

The annual precipitation recorded during the experiment ranged from 279.8 mm to 438.7 mm with an average of 380.0 mm. The years from 2007 to 2010 had relatively high precipitation (428.0 mm in average), while 2005, 2006, and 2011 had lower precipitation (315.9 mm in average). During these periods, most of the rainfall events did not exceed 25 mm per day, and the heaviest rainfall event recorded was 41.4 mm with the average rainfall intensity of 12.7 mm h^{-1}. Among these rainfall events, it was recorded that the instantaneous maximum rainfall intensity exceeded 110 mm h^{-1} but only lasted less than five minutes. Correspondingly, the potential evaporation in 2006 (from May 12 to October 19) and 2007 (from April 16 to October 21) were

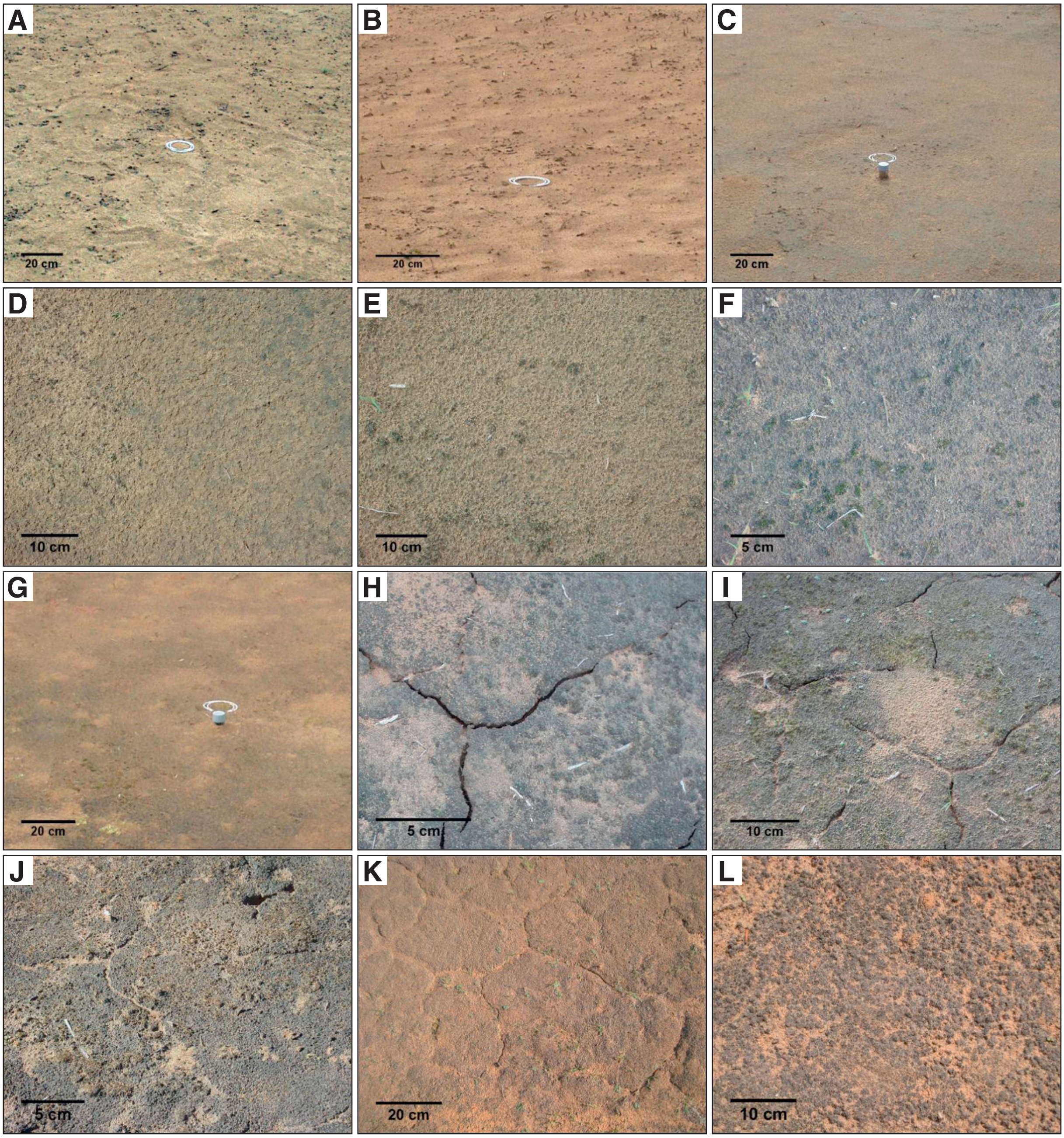

Fig. 2. Natural recovery process of BSCs from zero to near full coverage after the severe disturbance. (A) 2005-6-26, just after surface soil removal, (B) 2005-7-19, (C) 2006-5-26, (D) 2006-6-24, (E) 2006-7-24, (F) 2006-8-31, (G) 2006-9-22, (H) 2007-5-23, (I) 2007-7-23, (J) 2007-9-21, (K) 2011-7-26, and (L) 2012-5-24. The fine soil particles deposited on the soil surface in H to L were transported from the surrounding area by strong winds in winter and early spring rather than from the upper slope by runoff.

1536.7 mm and 1450.2 mm, respectively. The precipitation and atmospheric evaporative conditions in these years were not significantly different than the long-term average annual precipitation (409 mm) and potential evaporation (1337 mm) according to the results of the one-sample t test (precipitation: $t = -1.22$, $P = 0.27$; potential evaporation: $t = 3.62$, $P = 0.17$). This result implied that the long-term change of soil water conditions in this study did not seem to be caused by changes in climate but rather by the disturbance and recovery of natural BSCs.

The soil water content in the upper 40 cm fluctuated greatly and was closely correlated to the rainfall events, while the soil water content below 40 cm remained more stable and was not greatly influenced by the rainfall (Fig. 4). Because of rainfall events, the soil water content in the BSCs and the disturbed BSCs was not consistent over time and at different soil depths. Generally, the soil water content of the BSCs was higher than that of the disturbed BSCs, as reflected in Fig. 4. This figure also showed that the soil water content changed greatly with time, which agreed well with the restoration process of the disturbed BSCs from almost zero, with partial restoration in the first two years and then a fully re-covered soil surface in the next years (Figs. 2 and 3).

The differences of the soil water content between the BSCs and the disturbed BSCs were generally significant at 10 cm ($F = 7.02$, $P = 0.03$), 20 cm ($F = 6.74$, $P = 0.05$), 60 cm ($F = 8.10$, $P = 0.02$), and 70 cm ($F = 8.61$, $P = 0.01$); while they were not significant at the other depths ($P > 0.05$). It was also shown that the soil water content was significantly changed by the time effects ($F > 12.36$, $P < 0.001$) and the time and BSC interaction effects ($F > 1.57$, $P < 0.033$). In order to further evaluate BSC's effects on soil water content at different times, six representative dates in different years were selected for further analysis (Table 1). In Table 1, the absolute difference in the soil water content

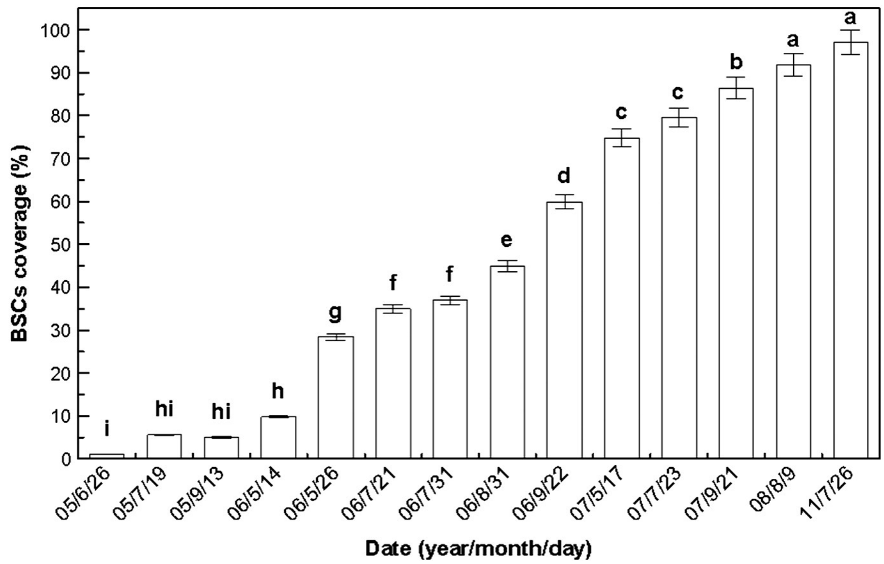

Fig. 3. Change of the BSC coverage after the severe disturbance carried out on June 26, 2005. The different letters on the bar indicate significant differences of the BSC coverage between these sampling dates at the 5% probability level.

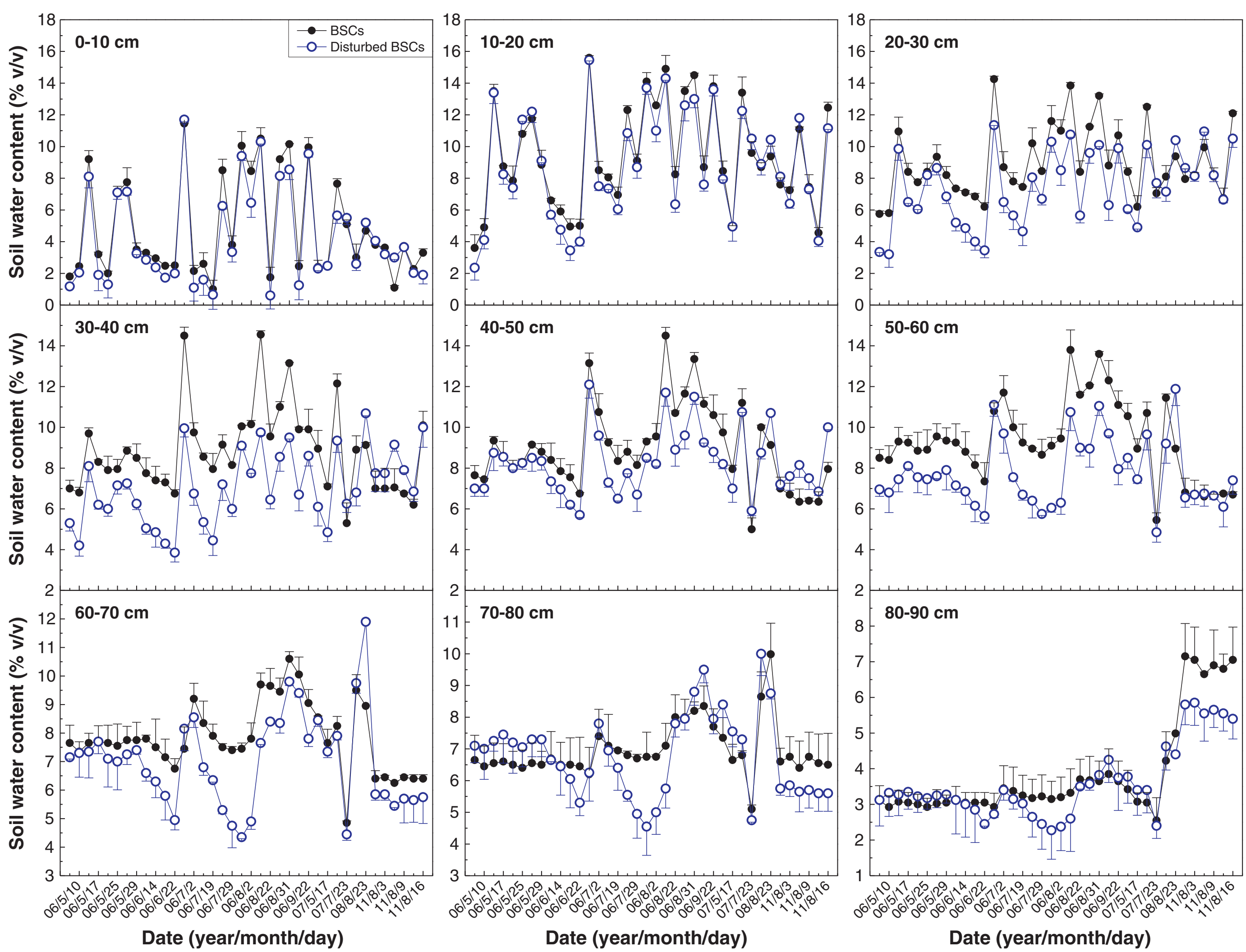

Fig. 4. Changes in soil water content of the BSCs and the disturbed BSCs at different soil depths after the severe disturbance carried out on June 26, 2005.

Table 1
Differences of soil water content (% v/v) between the BSCs and the disturbed BSCs at the six representative dates in different years.

Soil depth (cm)	2006-5-7			2006-10-16			2007-5-17			2007-9-19			2008-8-23			2011-8-16		
	Mean	SE[a]	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*
0–10	−0.63	0.22	0.042[b]	−0.10	0.29	0.762	0.00	0.01	0.843	−0.40	0.52	0.522	−0.53	0.51	0.409	−1.40	0.10	0.330
10–20	−1.25	0.43	0.042[b]	−0.50	0.17	0.007[c]	0.00	0.01	0.808	0.20	0.58	0.762	−1.05	0.01	0.410	−1.30	0.12	0.008[c]
20–30	−2.40	0.35	0.002[c]	−2.35	0.78	0.005[c]	−1.30	0.58	0.043[b]	−0.95	0.78	0.347	−1.30	0.91	0.294	−1.60	0.23	0.002[c]
30–40	−1.70	0.81	0.047[b]	−2.85	0.24	0.047[b]	−2.25	0.95	0.042[b]	−2.10	0.21	0.225	−1.55	0.82	0.049[b]	−0.10	0.29	0.762
40–50	−0.65	0.78	0.483	−1.55	0.95	0.242	−0.95	0.61	0.252	−1.25	0.89	0.297	−2.24	0.67	0.007[c]	2.05	0.32	0.004[c]
50–60	−1.55	0.53	0.418	−2.05	0.11	0.430	−1.50	0.50	0.419	−2.25	0.51	0.462	−2.93	0.52	0.043[c]	0.70	0.04	0.570
60–70	−0.50	0.23	0.045[b]	−0.10	0.92	0.911	−0.30	0.52	0.604	0.25	0.18	0.852	−0.85	0.92	0.706	−0.65	0.43	0.272
70–80	0.45	0.76	0.829	1.05	0.84	0.343	0.90	0.81	0.389	1.35	0.41	0.445	1.23	0.33	0.745	−0.90	0.64	0.292
80–90	0.05	0.76	0.980	0.70	0.04	0.578	0.65	0.78	0.502	0.80	0.02	0.736	1.25	0.32	0.743	−1.65	0.61	0.041[b]

[a] SE is standard error.
[b] Differences between the BSCs and the disturbed BSCs are statistically significant at the 5% probability level.
[c] Differences between the BSCs and the disturbed BSCs are statistically significant at the 1% probability level.

between the BSCs and the disturbed BSCs ranged from −2.9% to 2.1% with an average of −0.7%, while the averages in early 2006, the end of 2006, early 2007, and the ends of 2007, 2008 and 2011 were −0.91%, −0.86%, −0.53%, −0.48%, −0.89%, and −0.54%, respectively. The difference between soil water content of the BSCs and the disturbed BSCs greatly increased from 2006 to 2008 and then slightly decreased or remained stable from 2008 to 2011 (Fig. 5A). Fig. 5A showed that the BSC disturbance greatly decreased soil water content, although the reduction gradually weakened with time and almost disappeared at 2008. Similarly, the difference in the soil water content between the BSCs and the disturbed BSCs greatly decreased with soil depth at 0–40 cm and increased with soil depth at 40–90 cm (Fig. 5B), which implied that the greatest effects of BSC disturbance on soil water conditions occurred at approximately 40 cm.

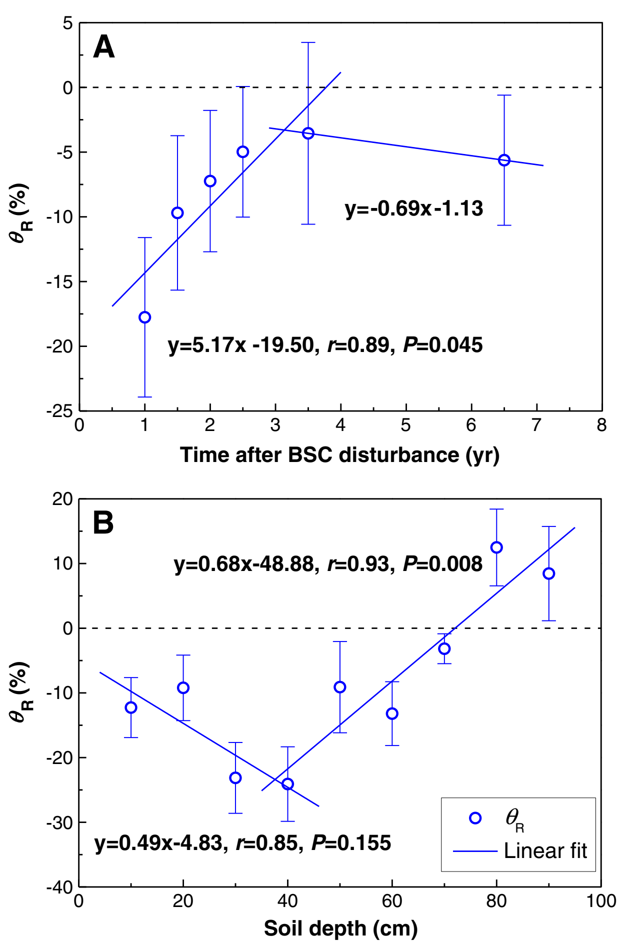

Fig. 5. Relative difference (θ_R) of soil water content between the BSCs and the disturbed BSCs changed with time (A) and soil depth (B). The relative difference (θ_R) was equal to the absolute difference (θ_E) divided by the soil water content of the BSCs.

4.3. Effects of BSC disturbance on soil water storage

The results of soil water storage in Fig. 6 were similar to those in Fig. 4, but the differences between the BSCs and the disturbed BSCs diminished in Fig. 6 due to the cumulative process, which most likely masks the small differences between them. The soil water storage was significantly influenced by the time effects ($F > 63.76$, $P < 0.001$) and by the interaction effects between the time and the BSCs ($F > 1.57$, $P < 0.033$) rather than by the BSC effects alone. The differences of the soil water storage between the BSCs and the disturbed BSCs were generally significant at 10 cm ($P = 0.03$), 20 cm ($P = 0.03$), 30 cm ($P = 0.04$), 40 cm ($P = 0.05$), 60 cm ($P = 0.05$), 70 cm ($P = 0.05$), 80 cm ($P = 0.04$), and 90 cm ($P = 0.04$); while they were not significant at 50 cm ($F = 0.69$, $P = 0.45$).

Based on the six representative dates in Table 2, the absolute difference of the soil water storage in the entire 0–90 cm soil layer ranged from −8.2 mm to −4.4 mm with an average of −6.3 mm; while the differences in early 2006, the end of 2006, early 2007, and the ends of 2007, 2008 and 2011 were −8.2 mm, −7.8 mm, −4.8 mm, −4.4 mm, −8.0 mm, and −4.9 mm, respectively. The difference of soil water storage between the BSCs and the disturbed BSCs increased greatly from 2006 to 2008 and then decreased slightly from 2008 to 2011 (Fig. 7A); whereas the difference of soil water storage linearly decreased from −12% at 10 cm depth to −19% at 40 cm and then linearly increased to −9% at 90 cm (Fig. 7B). In other words, the BSC disturbance decreased soil water storage and the greatest effects occurred in the fourth year after the disturbance and at 40 cm soil depth.

5. Discussion

5.1. Natural recovery of BSCs after disturbance

The recovery time of BSCs after disturbance was greatly determined by the BSC types (dominated by cyanobacteria or lichen or moss) and the climate conditions (e.g., precipitation and temperature). In this study, we found that it is possible to recover moss-dominated BSCs after severe disturbance without additional treatment under natural conditions, and the recovery process to near full coverage took approximately three years in the semi-arid region on the Loess Plateau of China (the mean annual precipitation is 409 mm; the mean annual temperature is 8.4 °C and ranged from −9.7 °C to 23.7 °C). Under natural conditions, Belnap (1993) found that the natural recovery rates of cyanobacteria- and lichen-dominated BSCs were very slow in the northwest of Moab (the mean annual precipitation is 393.5 mm; the mean annual temperature is 13.8 °C and ranged from 5.6 °C to 22.1 °C), Utah

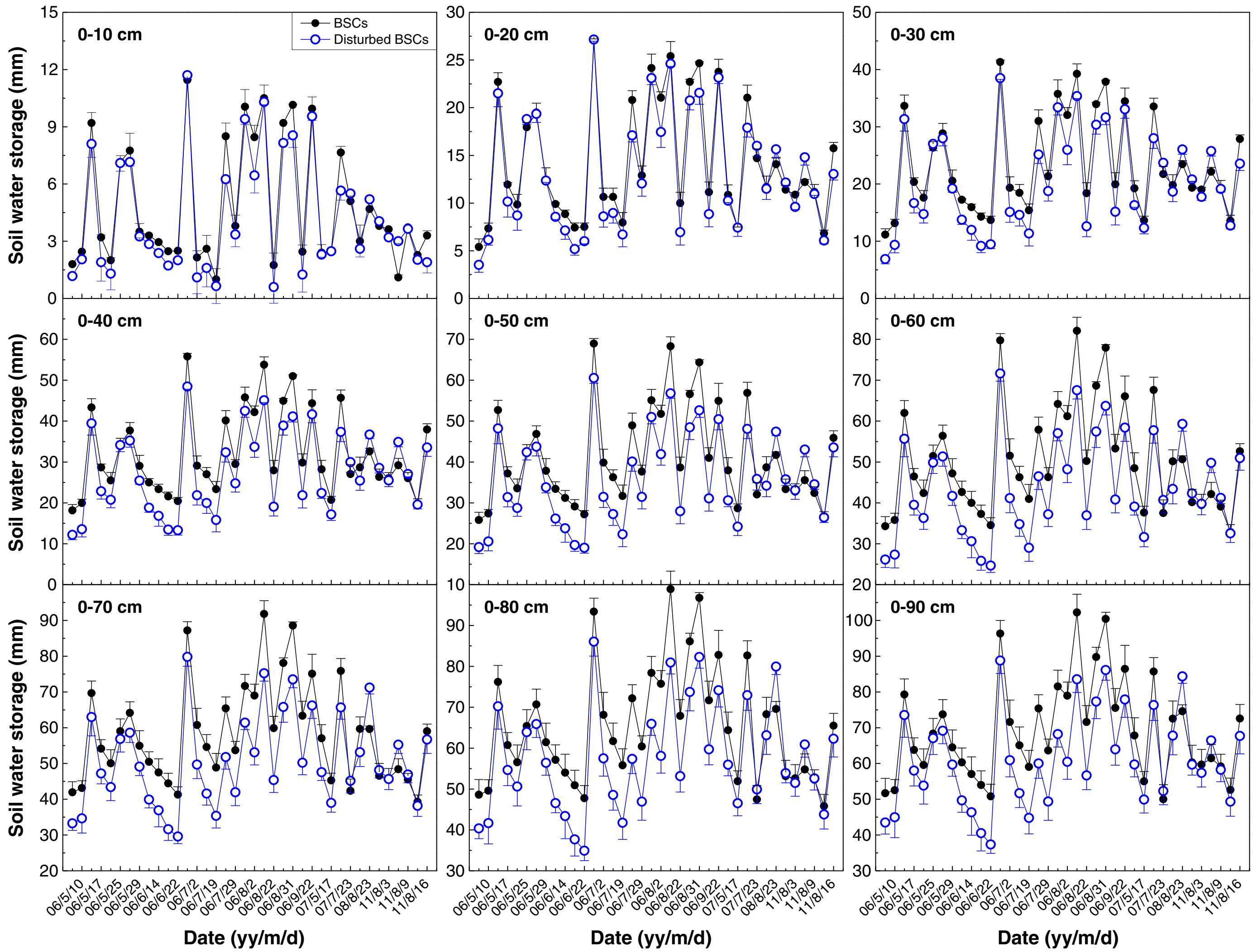

Fig. 6. Changes in soil water storage of the BSCs and the disturbed BSCs at different soil depths after the severe disturbance carried out on June 26, 2005.

in the United States. She also found that inoculation significantly hastened recovery for the cyanobacteria/green algal component, lichen cover, lichen species richness, and moss cover; however, the lichen and moss recoveries were minimal even with inoculation. Similarly, Briggs and Morgan (2012) assessed the recovery of lichen- and moss-dominated BSC diversity and cover in semi-arid grasslands in southern Australia (the mean annual precipitation is about 400 mm; the mean temperature is 3–15 °C in winter and 15–30 °C in summer), and they found that BSCs were initially slow to recover after soil disturbance. In southwestern Germany (the mean annual precipitation is 650 mm; the mean annual temperature is 9 °C and ranged from −1 °C to 24.8 °C), Langhans et al. (2010) also reported that a severely disturbed (BSCs were completely removed) soil surface originally covered by BSCs was recolonized by macro-cryptogams (bryophytes, lichens) two years after the strong disturbance, but the cyanobacteria- and algae-dominated BSCs returned at only 5% in comparison to the previous

Table 2
Differences of soil water storage (mm) between the BSCs and the disturbed BSCs at the six representative dates in different years.

Soil depth (cm)	2006-5-7			2006-10-16			2007-5-17			2007-9-19			2008-8-23			2011-8-16		
	Mean	SE[a]	P	Mean	SE[a]	P	Mean	SE[a]	P	Mean	SE[a]	P	Mean	SE[a]	P	Mean	SE[a]	P
0–10	−0.63	0.22	0.042[b]	−0.10	0.29	0.762	0.00	0.03	0.843	−0.40	0.52	0.522	−0.53	0.51	0.409	−1.40	1.10	0.330
0–20	−1.88	0.65	0.042[b]	−0.60	0.12	0.004[c]	0.00	0.09	0.919	−0.20	1.10	0.872	−1.58	1.52	0.410	−2.70	1.21	0.044[b]
0–30	−4.28	0.30	0.005[c]	−2.95	0.66	0.007[c]	−1.30	0.49	0.049[b]	−1.15	1.88	0.602	−2.88	1.43	0.357	−4.30	0.98	0.008[c]
0–40	−5.98	0.51	0.007[c]	−5.80	1.91	0.009[c]	−3.55	1.44	0.044[b]	−3.25	1.09	0.403	−4.43	2.25	0.307	−4.40	0.69	0.004[c]
0–50	−6.63	1.28	0.006[c]	−7.35	2.86	0.043[b]	−4.50	2.05	0.045[b]	−4.50	1.98	0.376	−6.67	1.92	0.231	−2.35	1.01	0.006[b]
0–60	−8.18	2.81	0.041[b]	−9.40	4.97	0.049[b]	−6.00	3.55	0.234	−6.75	2.50	0.407	−9.60	1.43	0.043[b]	−1.65	2.05	0.505
0–70	−8.68	3.05	0.044[b]	−9.50	5.89	0.248	−6.30	4.07	0.261	−6.50	2.68	0.485	−10.45	1.36	0.242	−2.30	2.48	0.452
0–80	−8.23	1.28	0.004[c]	−8.45	5.05	0.236	−5.40	3.26	0.240	−5.15	2.26	0.497	−9.22	1.69	0.442	−3.20	1.85	0.225
0–90	−8.18	1.28	0.003[c]	−7.75	4.01	0.043[b]	−4.75	2.48	0.045[b]	−4.35	2.24	0.412	−7.97	3.01	0.603	−4.85	1.24	0.009[c]

[a] SE is standard error.
[b] Differences between the BSCs and the disturbed BSCs are statistically significant at the 5% probability level.
[c] Differences between the BSCs and the disturbed BSCs are statistically significant at the 1% probability level.

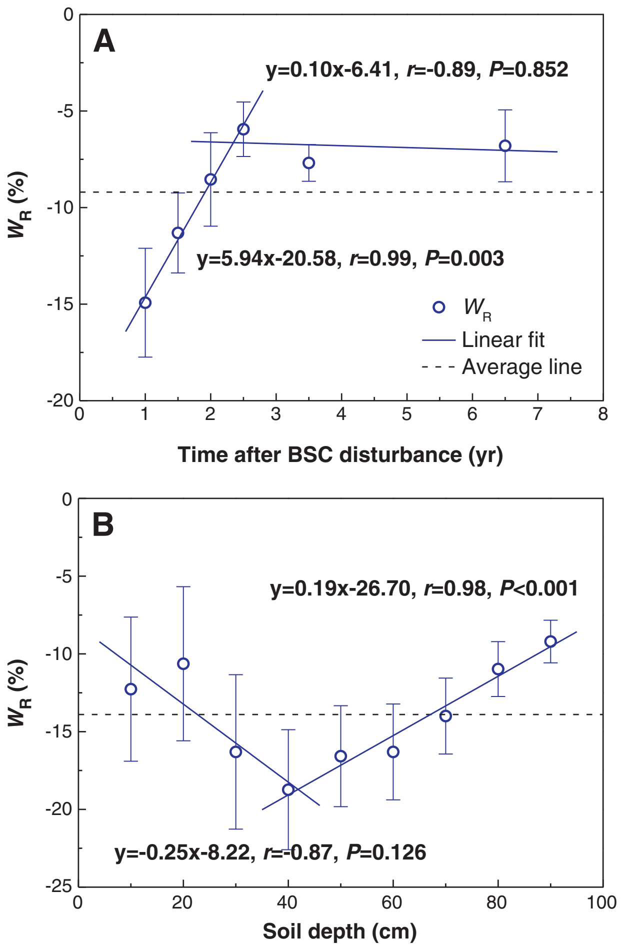

Fig. 7. Relative difference (W_R) of soil water storage between the BSCs and the disturbed BSCs changed with time (A) and soil depth (B). The relative difference (W_R) was equal to the absolute difference (W_E) divided by the soil water storage of the BSCs.

40% cover. Owing to the slow recovery rates of BSCs under natural conditions, several studies to test the feasibility and time required for culturing BSCs have been conducted under artificial conditions and using irrigation, fertilization, and inoculation. In Inner Mongolia, China, Chen et al. (2006) reported that algal crusts were formed in a short time and could resist the erosion of wind and rainfall 22 days after inoculation by *Microcoleus vaginatus* with direct inoculation onto an unconsolidated dune sand and irrigation by automatic sprinkling micro-irrigation facilities (the highest ground temperature was 47 °C and the lowest air temperature was 9 °C during the experiment). In the Tengger Desert (the mean annual precipitation is 186.2 mm; the mean annual temperature is 9.6 °C and ranged from −25.1 °C to 38.1 °C) in China, Tian et al. (2005) documented that the moss *B. arcticum* (R. Brown) B.S.G. completely covered the soil surface one month after inoculation by fragments of moss stems and leaves instead of spores. On the Loess Plateau of China (with 637.6 mm mean annual precipitation and 12.9 °C mean annual temperature), Xiao et al. (2011b) reported that it is feasible to artificially grow moss-dominated BSCs in a laboratory and that the artificial BSCs covered the soil surface almost completely after approximately 10 months.

Compared with the other studies, we attributed the longer restoration time of the BSCs after the disturbance in this study to the following four reasons. (1) The BSCs in this study were moss-dominated, which need more time to grow up and correspondingly more time to recover after disturbance compared with cyanobacteria- or lichen-dominated BSCs. (2) This study was conducted in a semi-arid region (cold desert) on the Loess Plateau of China, where the climate conditions (precipitation and temperature patterns) were possibly greatly different from the other regions (e.g., hot desert). (3) The disturbed BSCs in this study were 15 m^2 with a 5 m length and a 3 m width, which is greatly larger than the other studies (less than 1 m^2). The size of the disturbed area is very important to the restoration of BSCs after disturbance because the BSC seeds (spores, stems, and leaves) mostly came from the surrounding natural BSCs. Therefore, the larger area of disturbed BSCs possibly needs more time to recover because it would be more difficult to obtain BSC seeds from the surroundings. (4) We almost completely removed the BSC layer to simulate severe disturbance in this study; whereas the BSC layer was usually destroyed but left there in the other studies. The over-cleaning of BSCs possibly made the recovery process of BSCs longer in this study.

According to the experimental design, the BSC layer should have been removed completely during the disturbance. However, there were still some blocks of moss left (Fig. 2A and B), despite our attempts to be careful. Additionally, it was inevitable to leave some pieces of moss stems, leaves, and spores during the BSC disturbance because they were very fragile in the dry conditions. These moss blocks, stems, leaves, and spores functioned as the seeds in the restoration and development processes of BSCs after the disturbance. As a result, the development of disturbed BSCs started from the seed points and then spread to their surroundings. Therefore, these BSCs developed in patches rather than uniformly over the whole plot. In addition, the patches of BSCs could have been caused by their location (center or margin, upper slope or down slope) being affected by micro-environmental conditions, including moisture, sun radiation, temperature, and even wind.

As shown in Fig. 2H, I, J, and K, we found some remarkable cracks on the soil surface with clay, which was mainly deposited by dust deposition due to wind; these cracks were possibly caused by the alternating freezing and thawing in winter (approximate 110 days a year; during these days the soil temperature at 5 cm depth reached below to −18.3 °C during the night and up to 14.1 °C during the day, respectively) and the alternating drying and wetting in summer (the soil water content at 5 cm depth ranged from 2.2% to 15.7%, which depended on the near rainfall events). Another possible reason for the soil cracks was that the BSCs consumed a large proportion of surface soil water and subsequently intensified the soil surface shrinkage. These soil cracks possibly played an important role in the ecological function of the BSCs because they provided fast channels for water and energy flows (preferential flow).

Although the recovered BSCs were very similar to the natural BSCs in appearance (including density, height, and color of moss plants) and even in species composition in this study, it is reasonable to assert that the ecological functions of BSCs were not fully recovered. The development of natural BSCs is a long-term process, and their many important characteristics are invisible to the naked eye. This result was supported by Dojani et al. (2011), who found that the composition of recovering BSCs differed significantly from natural BSCs because they were dominated by light-colored cyanobacteria, while the natural BSCs were dominated by dark cyanobacteria.

5.2. Effects of BSC disturbance on soil water conditions

Although the runoff measurement was originally considered in the experimental design, no runoff was observed on the experimental site throughout the years due to the high soil water infiltration capacity of the loamy sand soil whether the soil was covered by crusts (physical or biological) or not. This result was confirmed by Xiao et al. (2007), who reported that the saturated hydraulic conductivities (measured by tension disk infiltrometer) of BSCs, removed BSCs, physical crusts, and dune sand in the study area were 96.3 mm h^{-1}, 188.7 mm h^{-1}, 194.0 mm h^{-1}, and 713.4 mm h^{-1}, respectively. Another possible reason was that a small amount of runoff was possibly generated on the plots under the extreme heavy rainfall events (which rarely occurred and usually lasted only a few minutes in the study area), but the runoff was retarded by the sand, debris, and micro-topography on the plots. In these situations, all the rainwater infiltrated into soil and no runoff was generated even in the heavy rainfall event (more than 40 mm in total amount and 60 mm h^{-1} in rainfall intensity).

We found that the BSC disturbance decreased surface soil water conditions (0–70 cm) but increased deep soil water conditions (80–90 cm) in this study through the following two possible ways. (1) The BSC disturbance greatly increased soil water evaporation, and surface soil water is easier to evaporate than deep soil water. (2) The BSC disturbance made more water infiltrate into deep soil because the BSC layer held more water at surface soil. Moreover, the greatest effects of the BSC disturbance on soil water conditions occurred at approximately 40 cm soil depth (Fig. 5B), which implied that the effect of soil suction at 40 cm was not anymore able to maintain the capillary continuity and the soil water below 40 cm moved further down while the soil water above 40 cm evaporated. Additionally, we found that the BSC disturbance greatly decreased soil water conditions and that the effects gradually weakened with time and almost disappeared in the fourth year due to the near full-coverage of BSC after the disturbance. Owing to the differences in BSC type, underlying physical soil crusts, soil properties, and climate conditions in the study area, our results were inconsistent with some researchers who reported that BSCs decreased infiltration and increased evaporation (Belnap et al., 2005; Xiao et al., 2011b; Zhang et al., 2008) and subsequently suggested that BSCs could be removed to improve soil water conditions. This result is correct for the BSCs developed on land with silt or clay soil, which function effectively in the partition between infiltration and runoff in rainfall events due to their low infiltration capacity. However, the BSCs developed on loamy sand soil with very high infiltration capacity in this study, resulted in complete rainwater infiltration and did not generate overland flow over the plots in any rainfall event. Therefore, there were no differences in the amount of water infiltration between the BSCs and the disturbed BSCs. Any possible reduction of infiltration by BSCs was completely masked by the high water infiltration capacity of loamy sand soil (Eldridge, 1993; Eldridge and Greene, 1994; Williams et al., 1999). Another effect of BSCs on infiltration may occur in this situation as the BSCs decreased the water infiltration depth because the BSC layer held more water by their higher water holding capacity (Wang et al., 2006). Even so, the amount of infiltration did not differ between the BSCs and the disturbed BSCs. Because the BSCs and the disturbed BSCs had the same infiltration, the difference in soil water storage was caused by different water evaporation events between the two treatments. In other words, the BSC disturbance did not change the amount of water infiltration but possibly did increase water evaporation and therefore reduced the soil water storage. This speculation was verified by Xiao et al. (2010), who reported that although the amount of evaporation was only slightly higher when the BSCs were present, the BSCs greatly decreased water evaporation over the first several days when soil water content was high. The effects of BSCs in reducing water evaporation could be attributed to the capping of the soil surface by BSCs (George et al., 2003) or the high proportion of finer particles in BSCs (Zhang et al., 2008).

The results of this study indicated that the BSC disturbance aggravated the poor soil water conditions in the semi-arid environment on the Loess Plateau of China. In other words, we concluded that the presences of BSCs improved soil water conditions compared with the disturbed BSCs. Although the effects of BSC disturbance on soil water conditions were not fully investigated before, there was a lot of evidence supporting that the presence of BSCs improved soil water conditions (Gao et al., 2010; Kidron and Vonshak, 2012). The increased soil water storage of BSCs in surface soil or shallow soil was mainly attributed to their higher water holding capacity, which was 3 to 9 times of the non-BSCs (Almog and Yair, 2007; Wang et al., 2006), or greater infiltrability caused by increased porosity, enhanced aggregate stability and improved physical structure (Mager and Thomas, 2011; Menon et al., 2011; Rossi et al., 2012). Our results implied that BSCs improved soil microhabitat and increased the availability of soil moisture to shallow rooted shrubs, herbs and soil fauna in artificially re-vegetated ecosystems on the Loess Plateau of China (Wang et al., 2006). Although the absolute value of soil water content increased by the BSCs was less than 1% at some soil depths, this part of soil water is very important for annual grasses, small shrubs, soil microbes and animals, and even live components of BSCs in dry environments due to the very low soil water content (less than 5% in most cases) of the loamy sand soil in the study area.

In this study, the soil water content of the BSCs and the disturbed BSCs was mainly measured during the periods from May to October due to the following three reasons. Firstly, the most rainfall in the study area occurred in summer (accounted more than 90% of annual precipitation), whereas very little snow occurred in winter. Secondly, the soil water was completely frozen in winter because of the very low daily mean air temperature and soil temperature, which reached −19.4 °C and −14.6 °C, respectively. Lastly, the dry environment and low temperature made the live components (such as moss, fungi, and bacteria) of BSCs inactive. Owing to the above three reasons, the BSCs almost slept in winter and therefore their effects on soil water conditions in winter were not investigated in this study. However, it should be noted that the effects of BSCs on soil water conditions were possibly dependent on seasonal change. We found that the BSCs were complete active (in deep green or bright color) in the rainy season from June to September due to the sufficient moisture and the high temperature; while the BSCs were partly activated (in gray or dark color) in the several months before or after the rainy season (including April, May, October, and November) due to the limited moisture and the moderate temperature. In other words, BSCs possibly have greater effects on soil water conditions during the rainy season and lesser effects during the non-rainy season. Additionally, this study was conducted on the Loess Plateau of China, where the climate conditions are characterized as rare snow and very low temperature in winter and sufficient rainfall and high temperature in summer. Thus, the results about BSC's effects on soil water conditions would possibly be greatly different in other regions due to the different climate conditions and different type of BSCs (cyanobacteria- or lichen-dominated BSCs).

Due to the limitation of measurement methods (TRIME-IPH, IMKO in Germany), we measured soil water content by hand and at only three points in each plot. The results would be more reliable and solid if more sites in each plot could be monitored in further studies, especially if the soil water content could be automatically measured and collected by the use of a soil water content probe and data logger. Moreover, this study was based on a plot scale experiment, in which the plots were hydraulically isolated from one another but not in relation to their surroundings. Therefore, further studies in larger spatial scale, for example slope or micro-basin scales, would be very necessary.

6. Conclusions

From our experiments, we concluded the following: (1) it is possible to recover natural moss-dominated BSCs after severe disturbance under natural conditions, and the recovery process to BSC full-coverage took approximately three years; (2) the BSC disturbance greatly decreased soil water content by up to 18% and the effects gradually weakened with time and almost disappeared at the fourth year due to the near full coverage of BSCs after the disturbance; (3) the BSC disturbance decreased surface soil water content (0–70 cm) by up to 24% but increased deep soil water content (80–90 cm) by up to 13%; and (4) the BSC disturbance decreased soil water storage at 0–90 cm by 7.8 mm, 4.4 mm, 8.0 mm, and 4.9 mm in the second, third, fourth, and seventh years, respectively.

From these results, we concluded that the BSC disturbance degraded soil water conditions in the three to four years following the disturbance. Therefore, the artificial destruction of natural BSCs should not be recommended as a land management practice for the improvement of soil water conditions during re-vegetation and desertification control in the semi-arid environment on the Loess Plateau of China, and most probably in other cold semi-arid regions.

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